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What we learned from EMMA

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on behalf of the EMMA collaboration
ASTeC/STFC Rutherford Appleton Laboratory
22 September 2014
FFAG workshop 2014, BNL

- EMMA stopped its operation in December 2012.
- Since then, several funding requests have been submitted without success.

Overview

- Introduction of non-scaling FFAGs
- Highlights for the last few years
- What we learned from EMMA

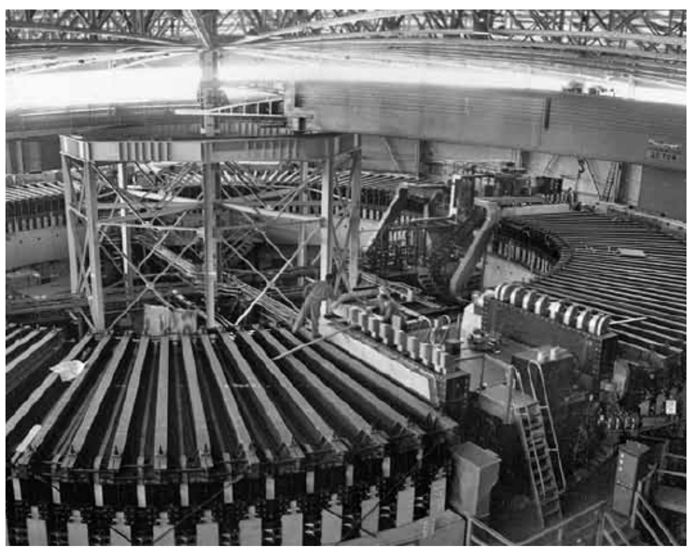
Introduction

From weak to strong focusing

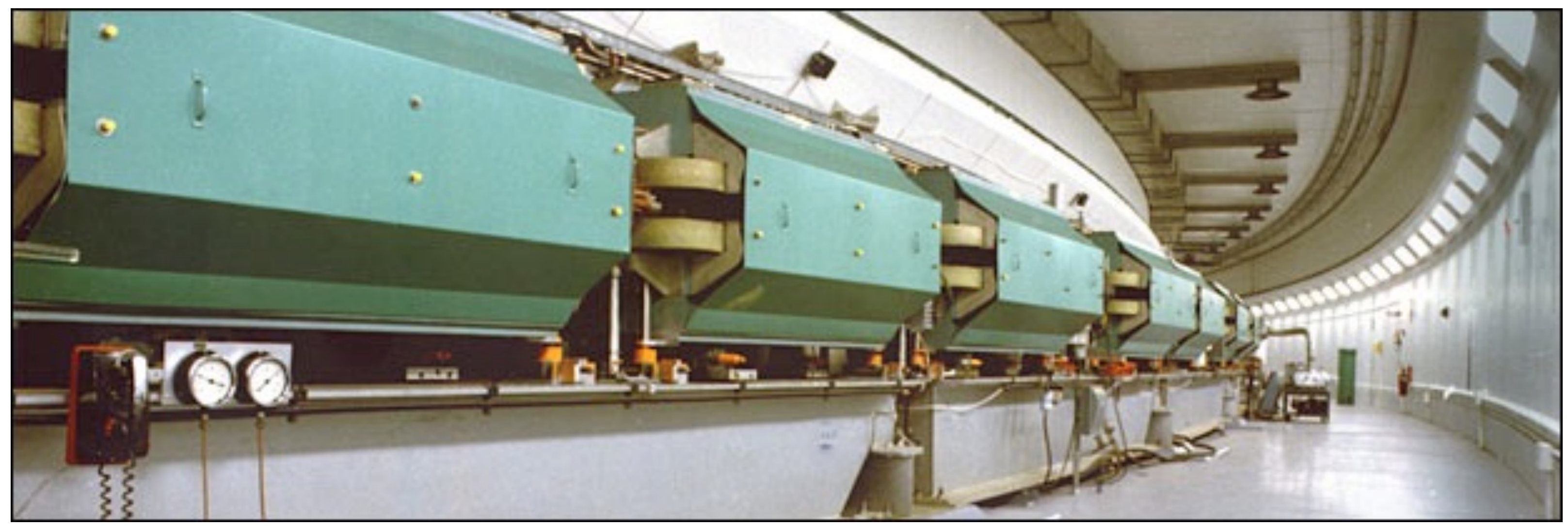
Weak focusing synchrotron

Strong (or Alternating Gradient) focusing

Bevatron



Brookhaven AGS



Small beta function

Beam size becomes small for the same emittance

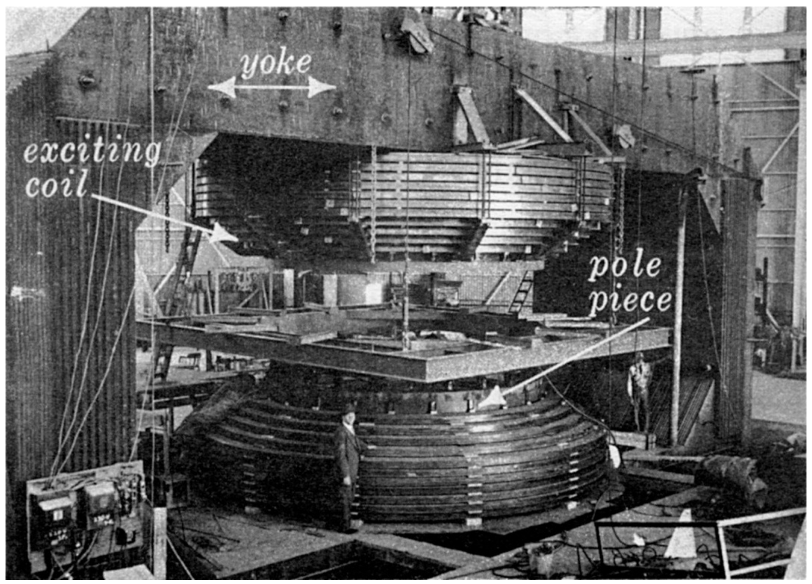
Small dispersion function

Orbit shift due to momentum spread becomes small

From cyclotron to FFAG

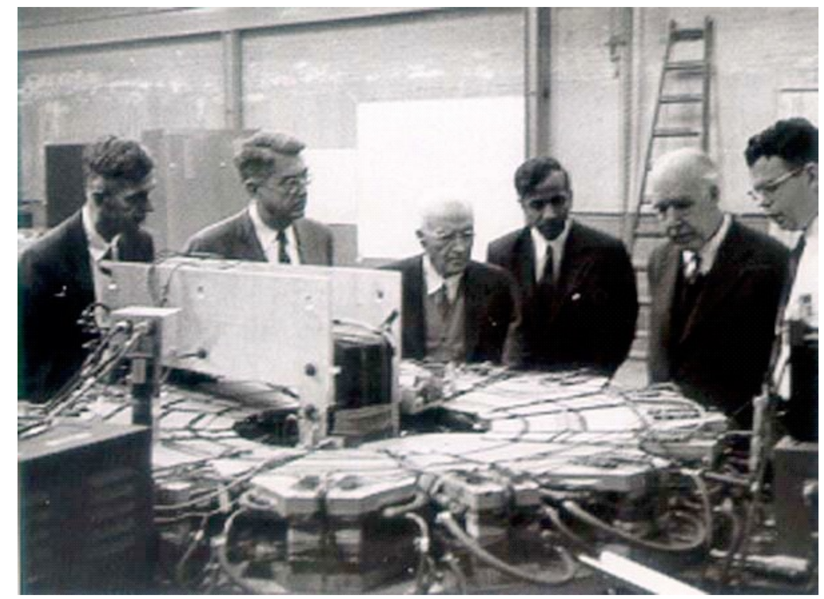
Cyclotron

Synchro-cyclotron



184 inch Berkley synchrocyclotron

Fixed Field Alternating Gradient (FFAG)



MURA electron FFAG

Strong focusing

Beam size is small

Orbit excursion is small

Small chamber

Small magnets

Higher energy

(in addition) Constant tune

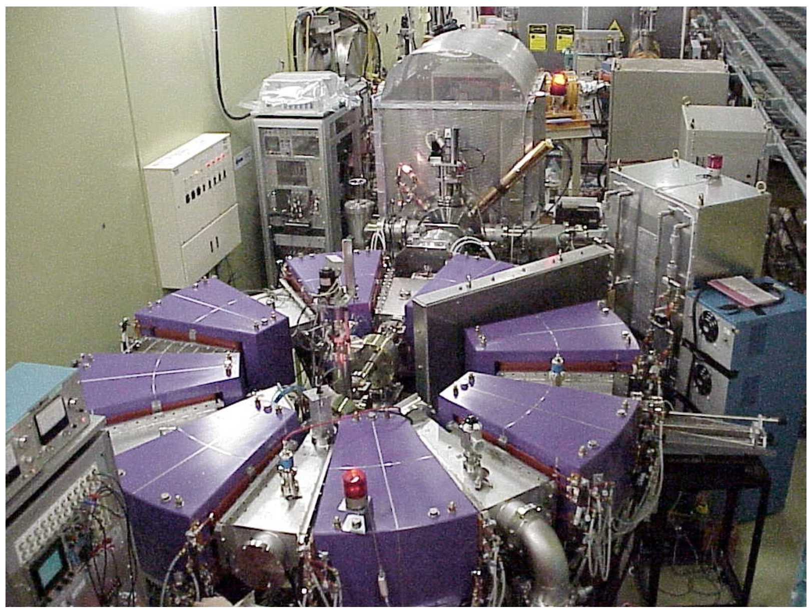
Avoid resonance crossing

Pulsed operation

Low average current

From scaling to non-scaling FFAG

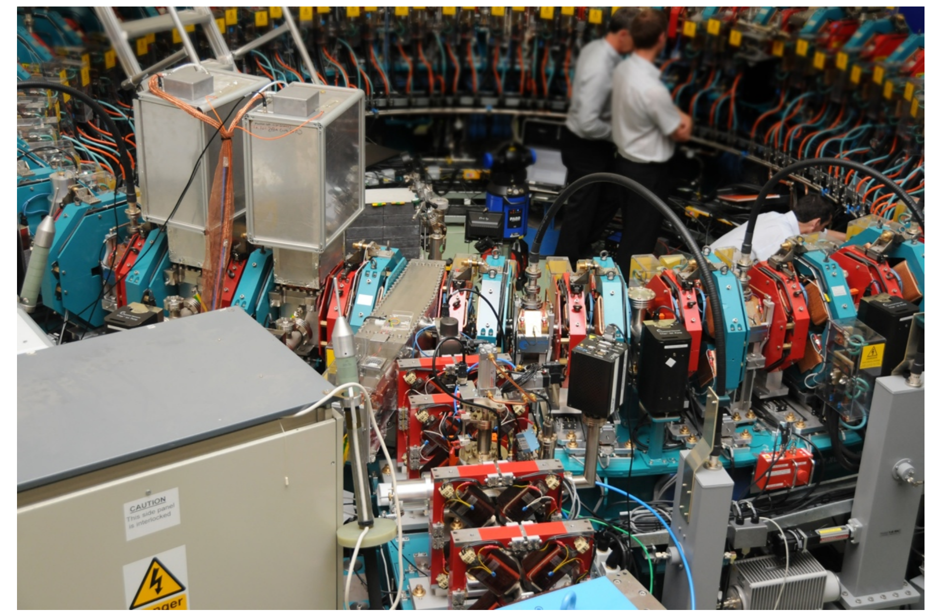
Scaling FFAG



KEK PoP
FFAG

Non-scaling FFAG

EMMA



Stronger focusing

Beam size is small
Orbit excursion is small

→

Small chamber
Small magnets
Higher energy

~~Constant tune~~

Cannot avoid resonance crossing

Pulsed operation

Low average current

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Motivation behind

Accelerator for muons

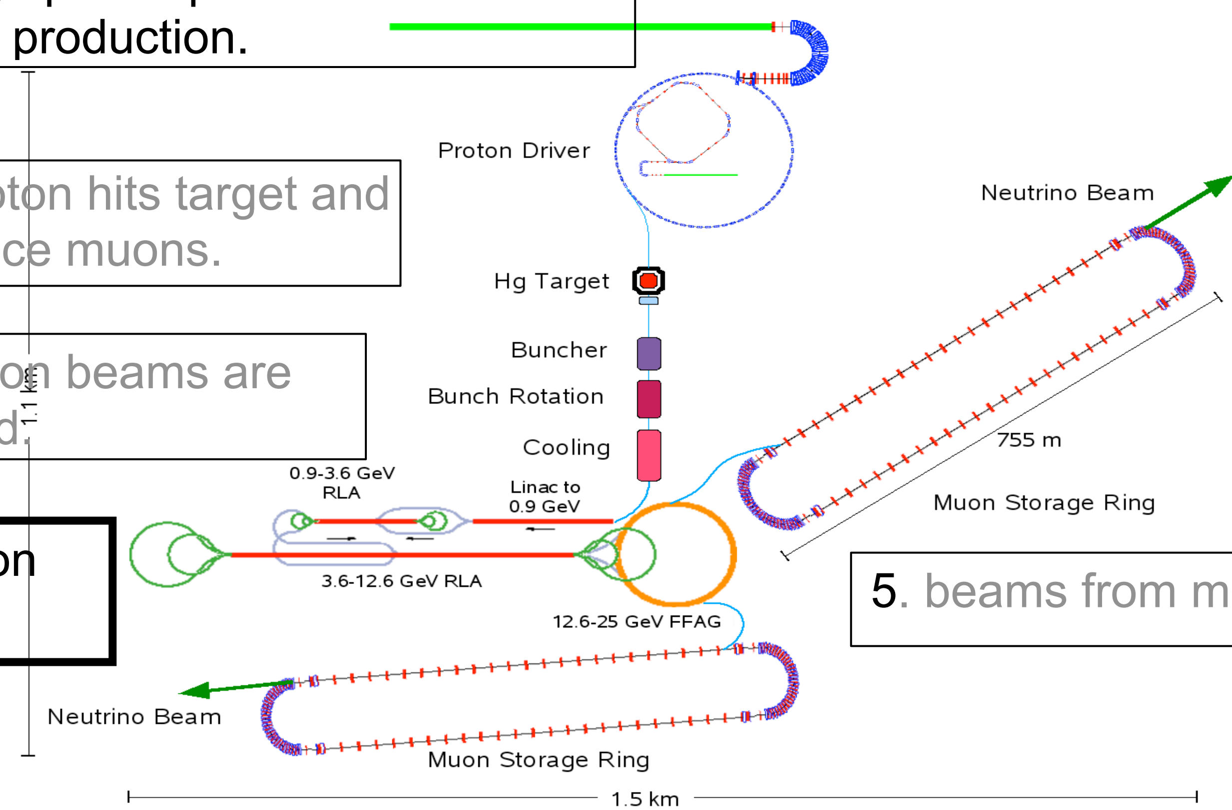
1. High power proton beam for muon production.

2. Proton hits target and produce muons.

3. Muon beams are cooled.

4. Acceleration of muon beams to 20-50 GeV.

5. beams from muon decay.



Muon beams does not stay in FFAG for long

Resonance may be harmless

Emittance of muon beams is huge

Large machine acceptance is required

High momentum gain is preferable

Orbit excursion should be as small as possible

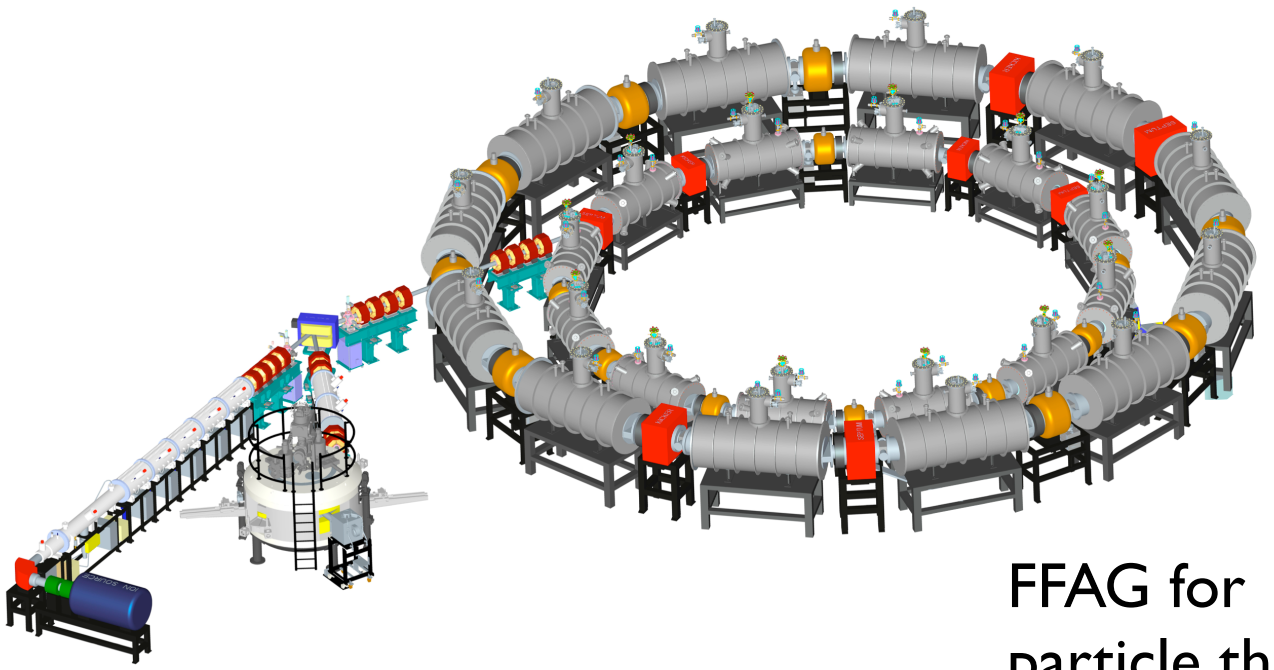
From concept to demonstration

What a nice idea!

Fixed field accelerator (like cyclotron) with the size of synchrotron magnets.

Idea was initially proposed as a muon accelerator for a neutrino factory.

Applications of the same concept were further considered.



FFAG for particle therapy

EMMA (Electron Model for Many Applications).

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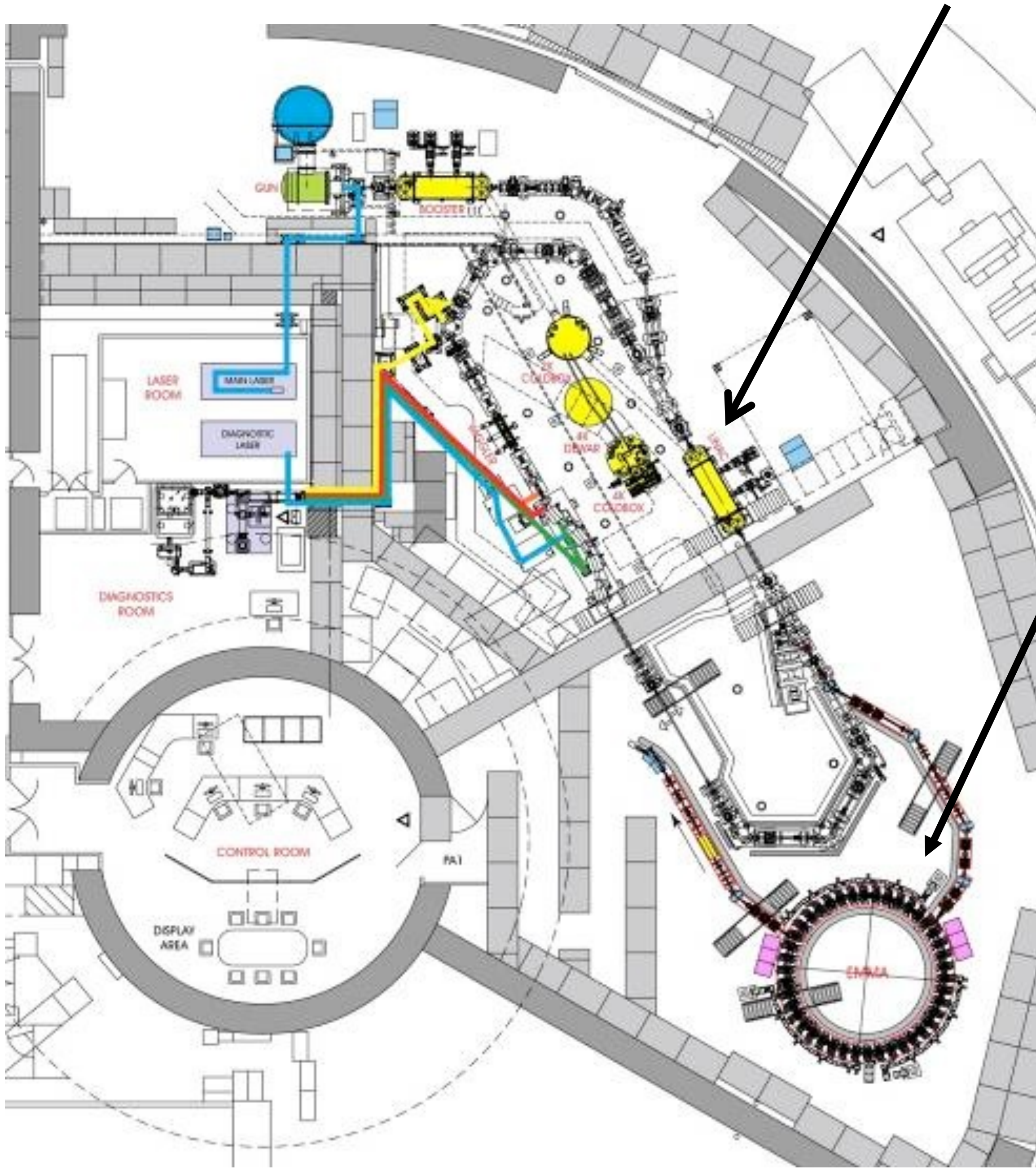
Highlights for the last few years

Home of EMMA

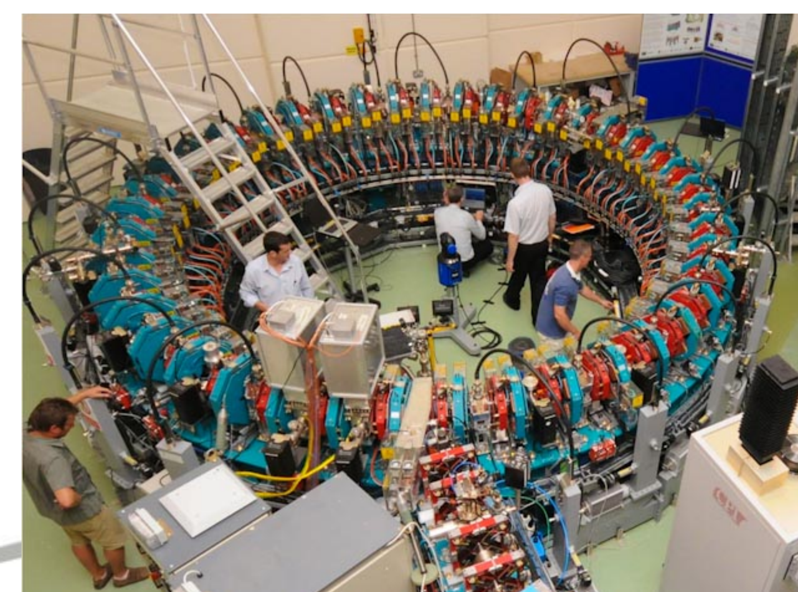
Built at Daresbury Laboratory in the UK

ALICE (Accelerators and Lasers in Combined Experiments)

EMMA



Parameter	Value
Particle	electrons
Momentum	10.5 to 20.5 MeV/c
Cell	42 doublet
Circumference	16.57 m
RF Frequency	1.301 GHz
RF voltage	2 MV with 19 cavities



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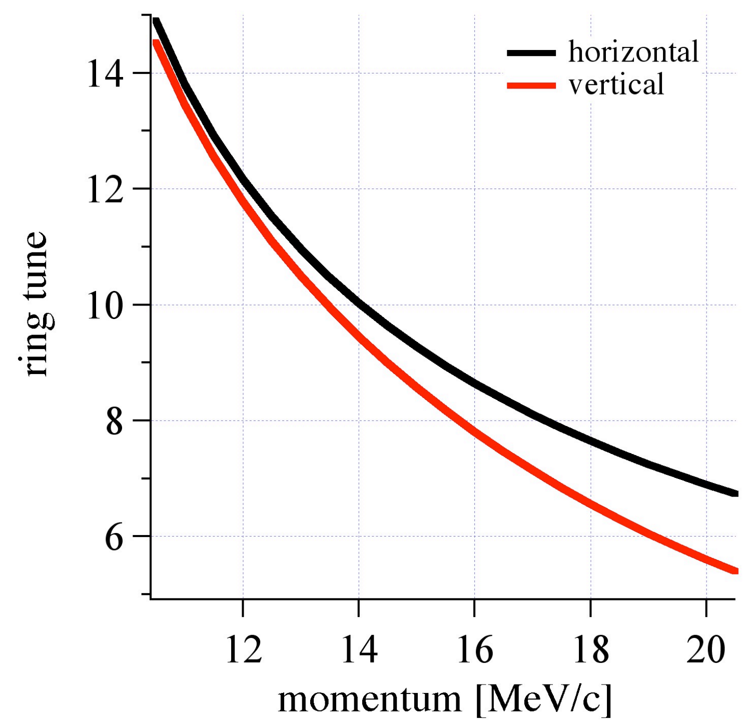
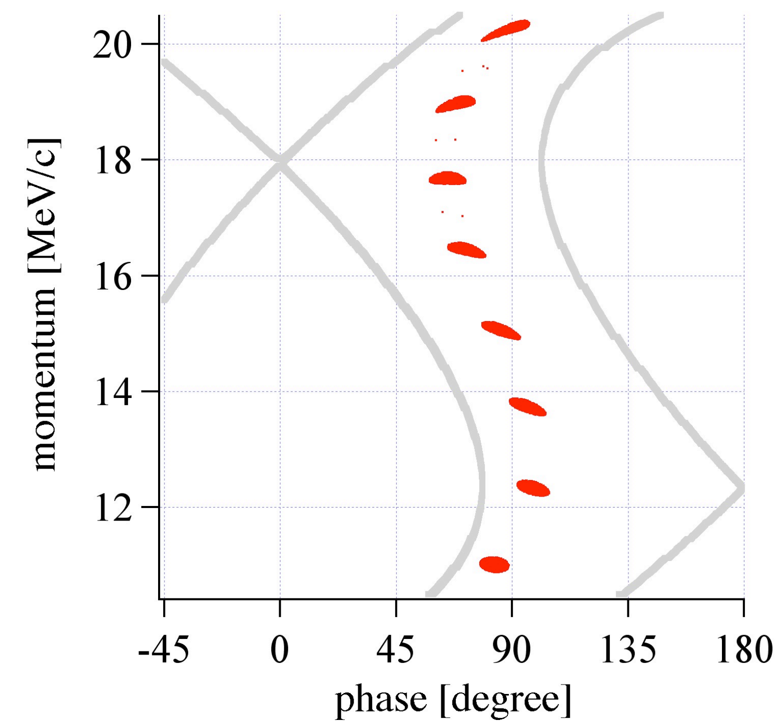
Three main goals

(1) Fast acceleration with resonance crossing.



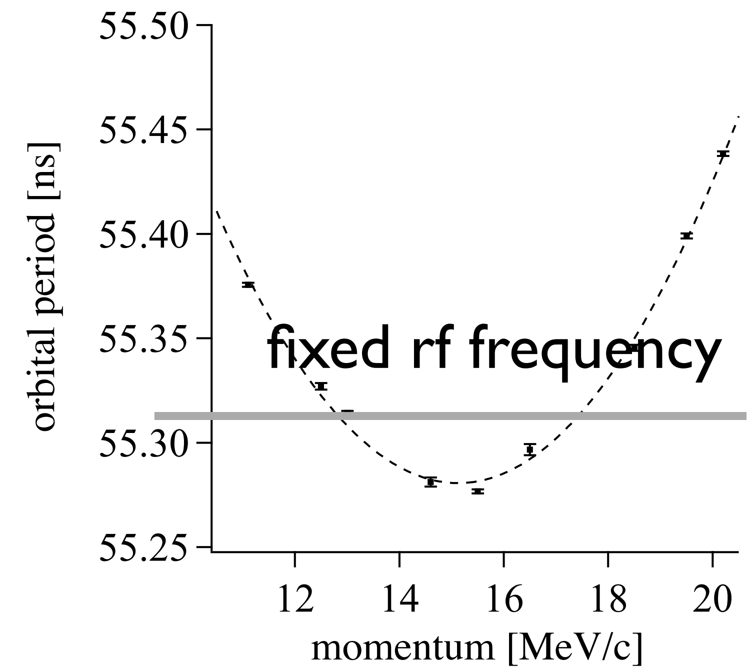
(2) Serpentine channel acceleration.

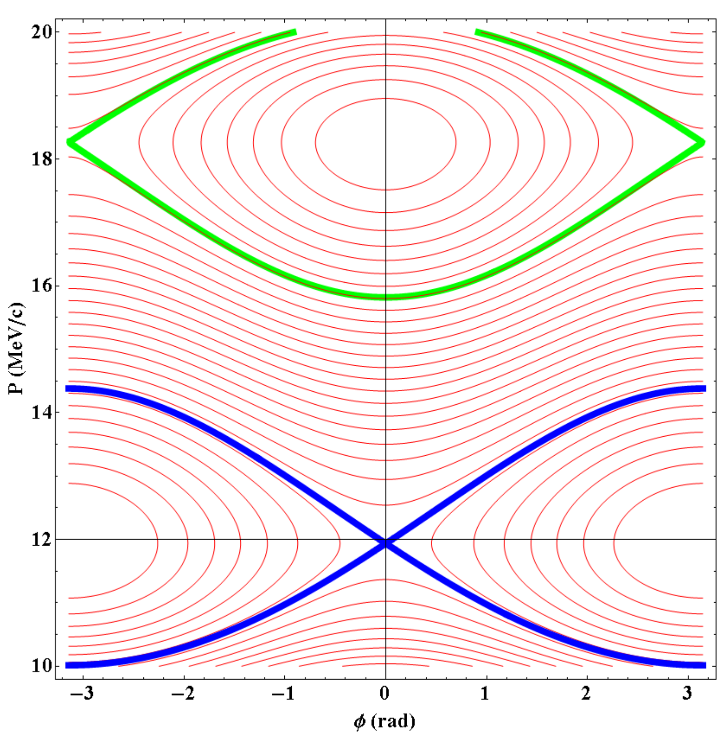


(3) Large acceptance (strong focus.)

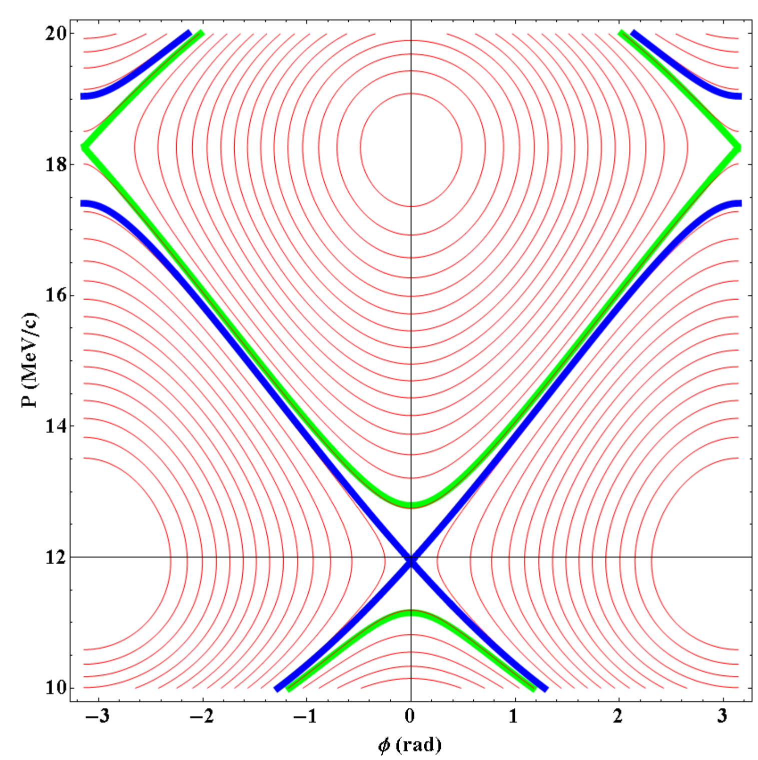
Serpentine channel

When orbital period is almost constant and has parabolic dependence on momentum, path outside rf buckets emerges in longitudinal phase space.

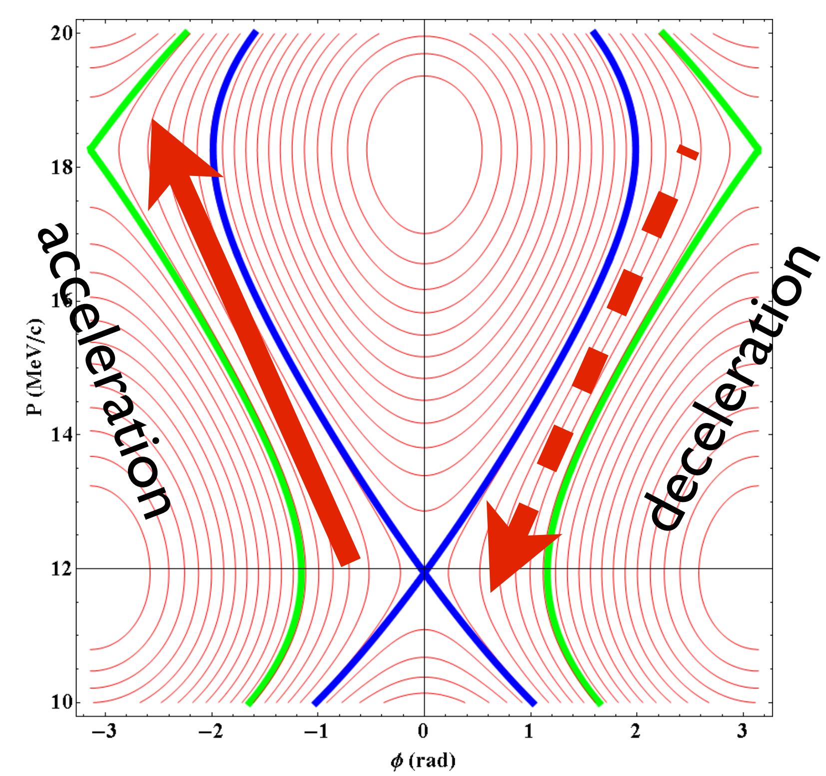




rf voltage is not enough



at critical rf voltage



rf voltage is enough to open channel

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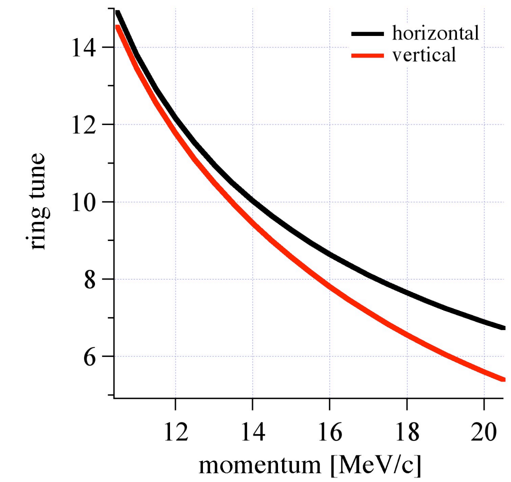
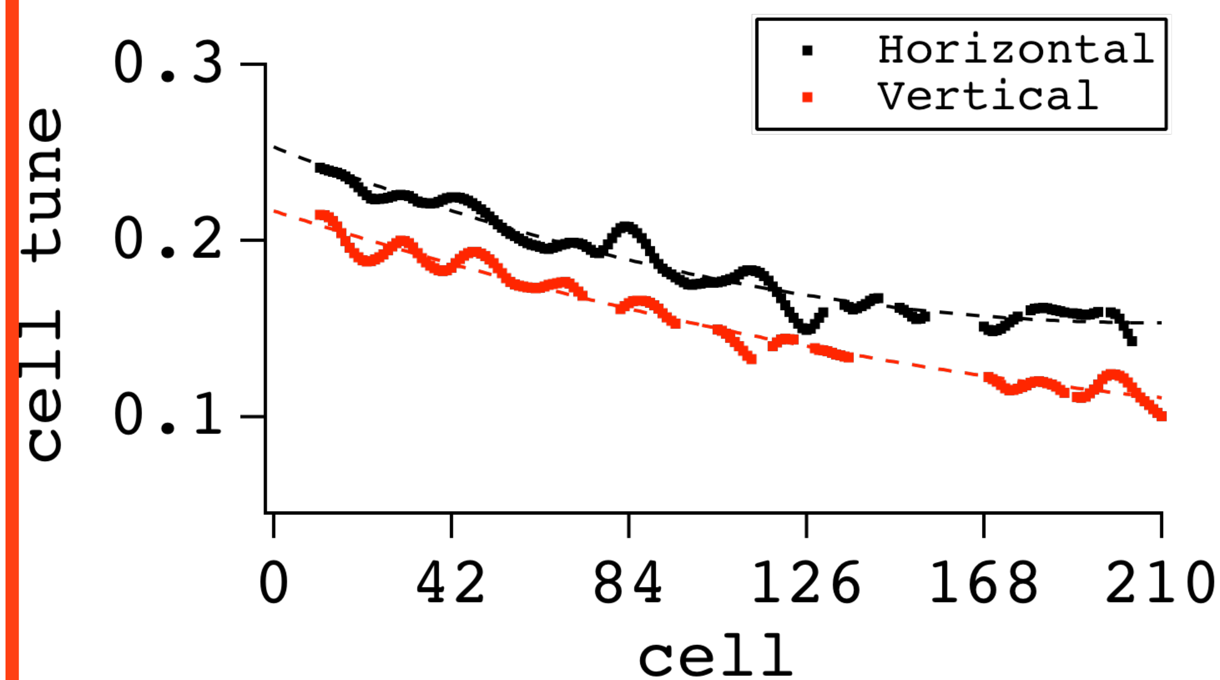
Acceleration with resonance crossing

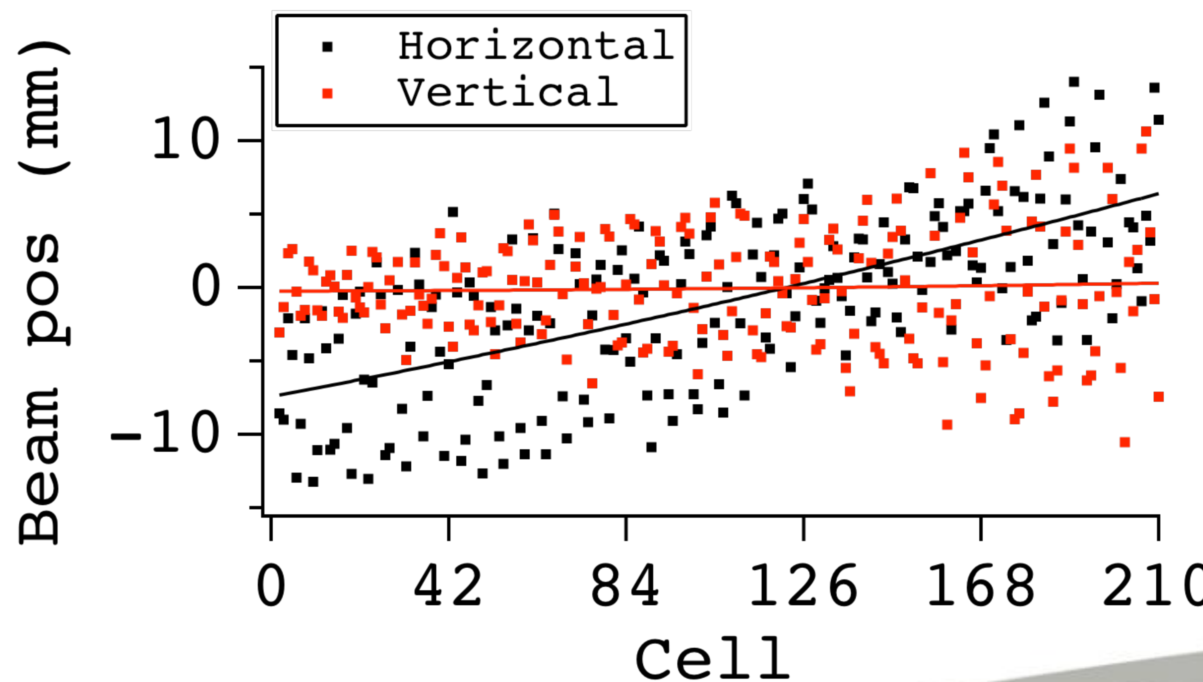
Rapid acceleration with large tune variation

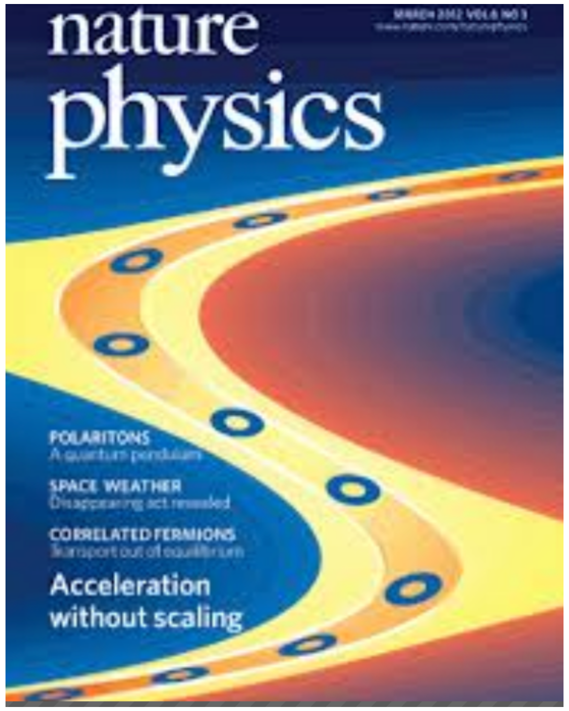


Highlight 1

Tune decreases and hor. orbit increases monotonically in measurement.



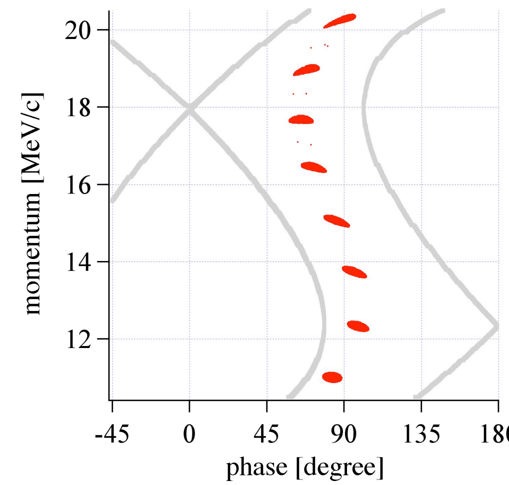




Nature Physics, March 2012

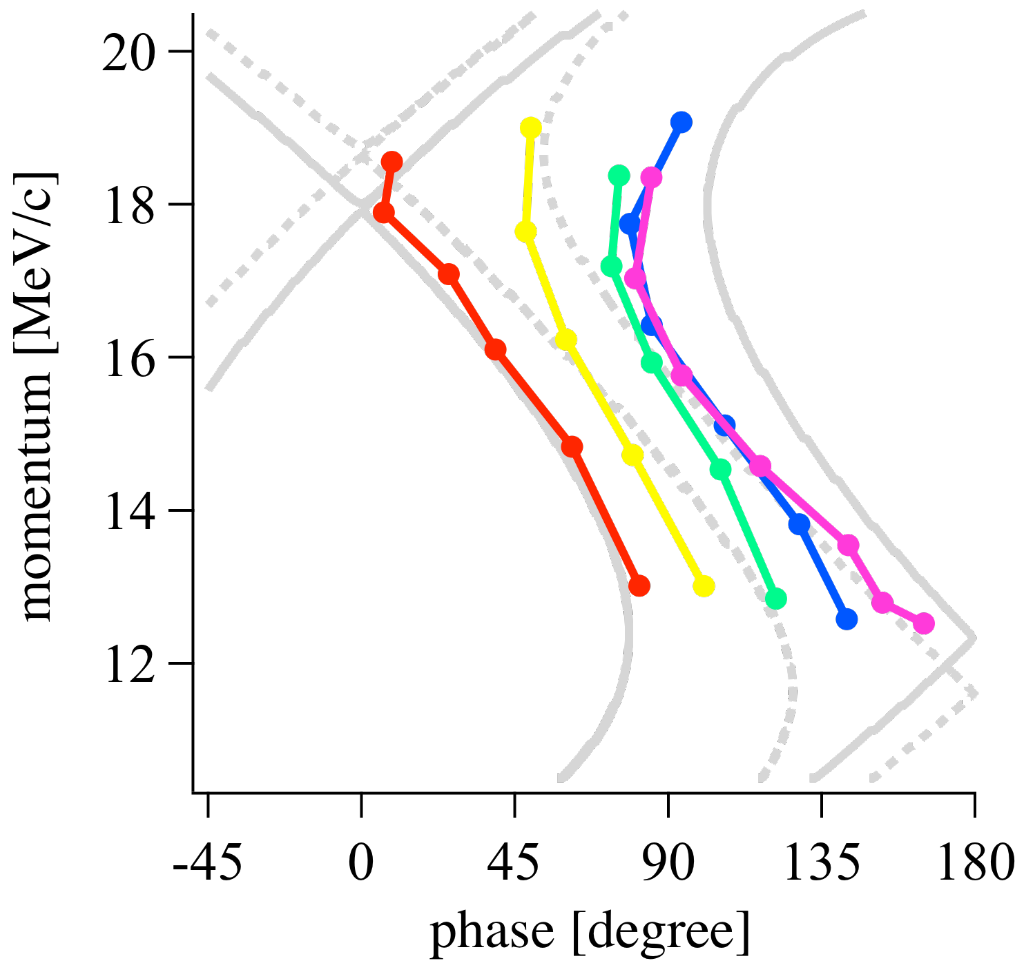
Serpentine channel acceleration

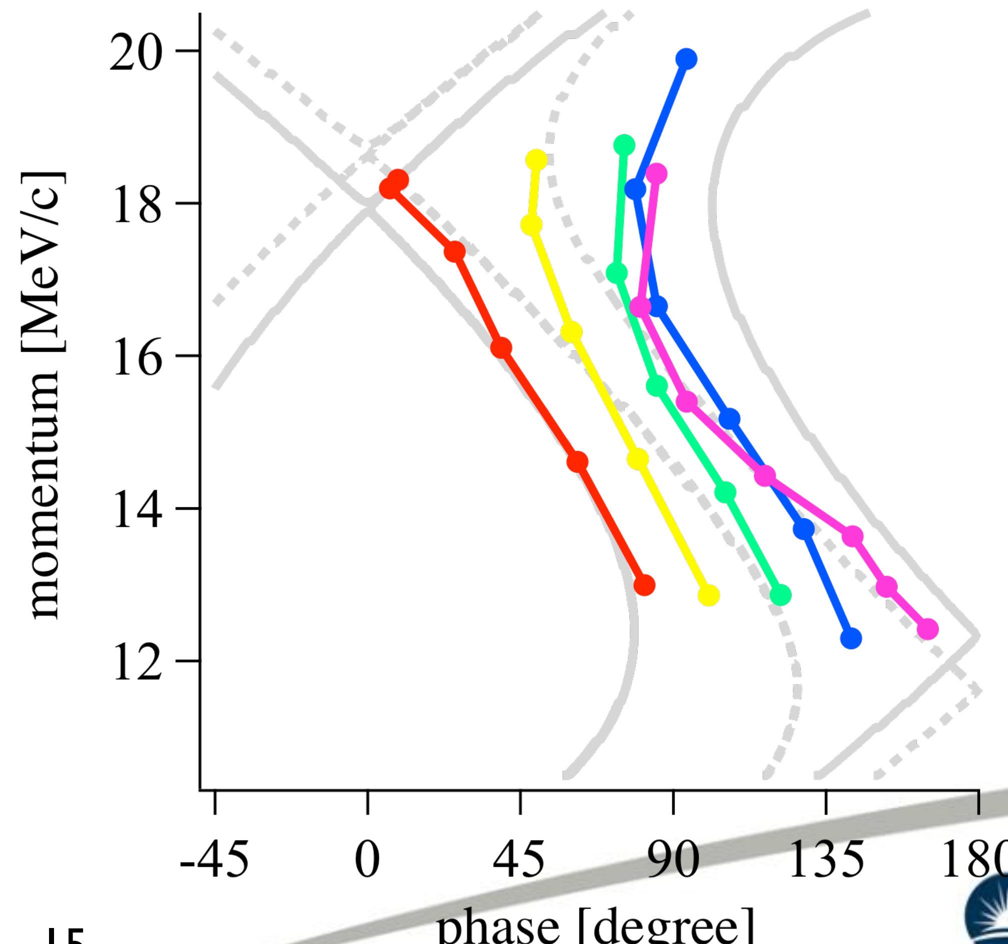
Serpentine channel acceleration outside rf bucket



Highlight 2

Longitudinal trajectory measured experimentally.



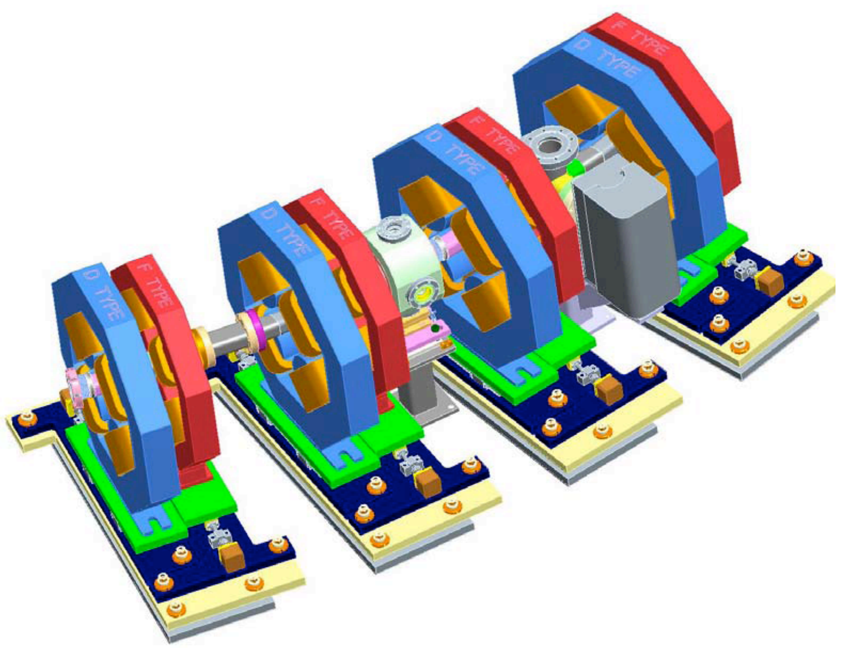


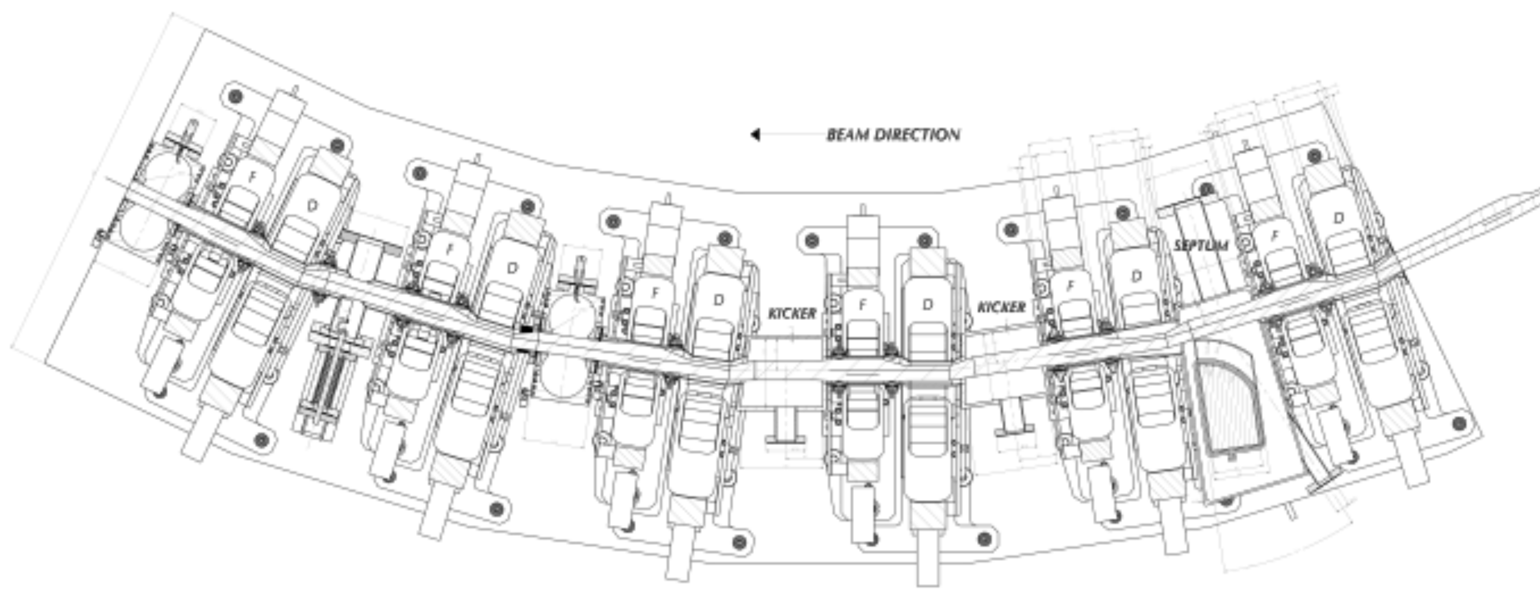
What we learned

What we learned (1)

very small dispersion lattice

"Cyclotron" with synchrotron size magnets.





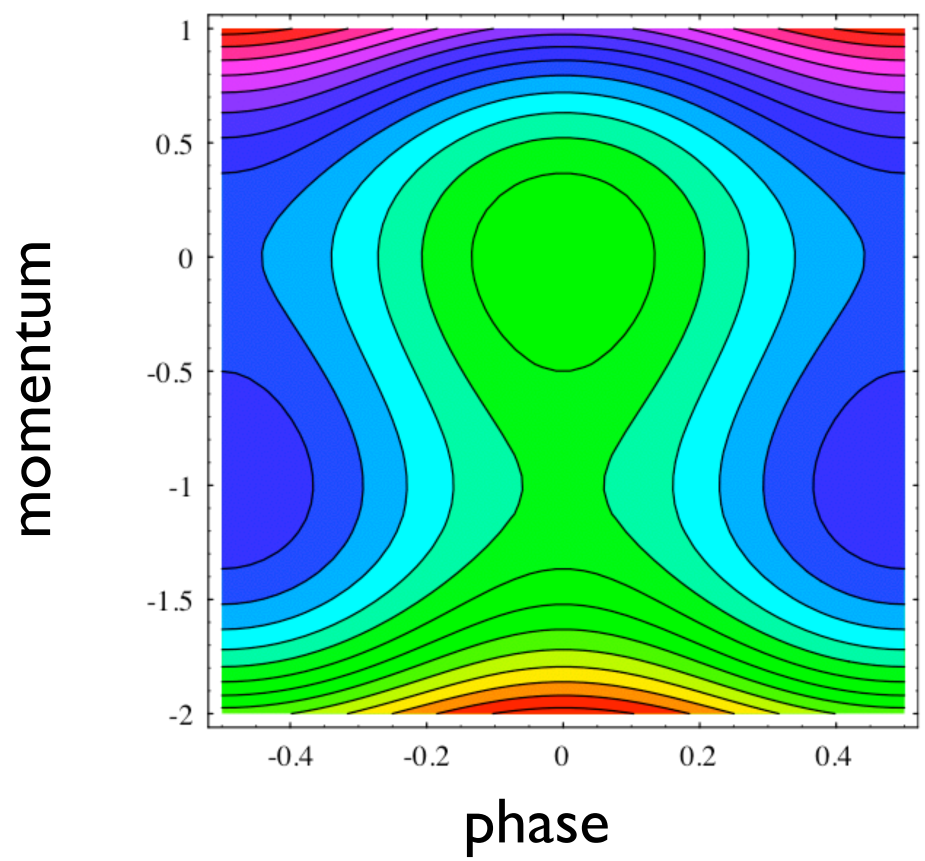
Very small orbit excursion can be realised by very small dispersion function lattice.

Optics is stable.

What we learned (2)

almost isochronous lattice

For ultra-relativistic particles, small orbit excursion makes the lattice almost isochronous.



Fixed frequency rf can be used for acceleration within a short time period.

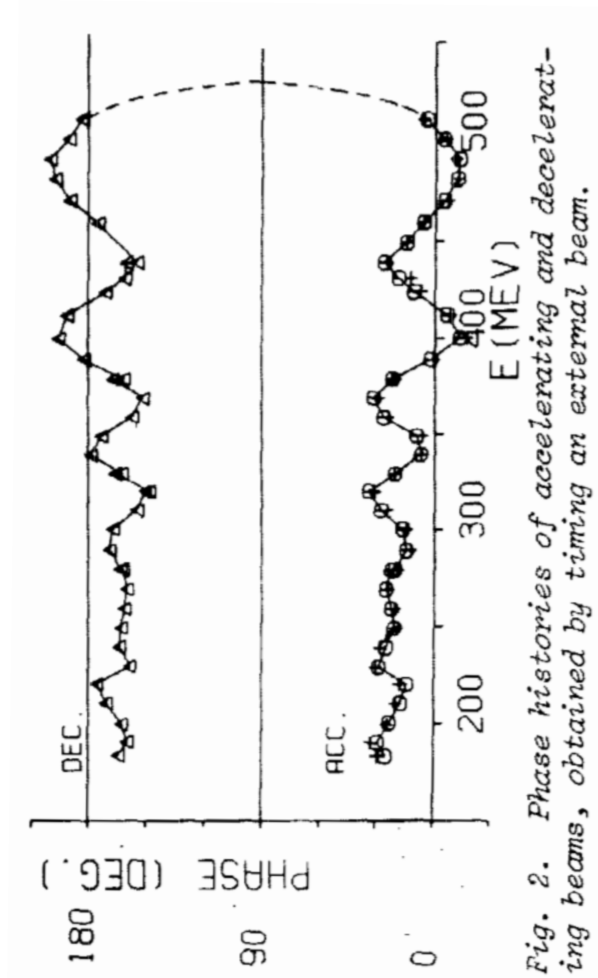


Fig. 2. Phase histories of accelerating and decelerating beams, obtained by timing an external beam.

Dynamics is very similar to longitudinal motion in a nearly isochronous cyclotron. (by Craddock)

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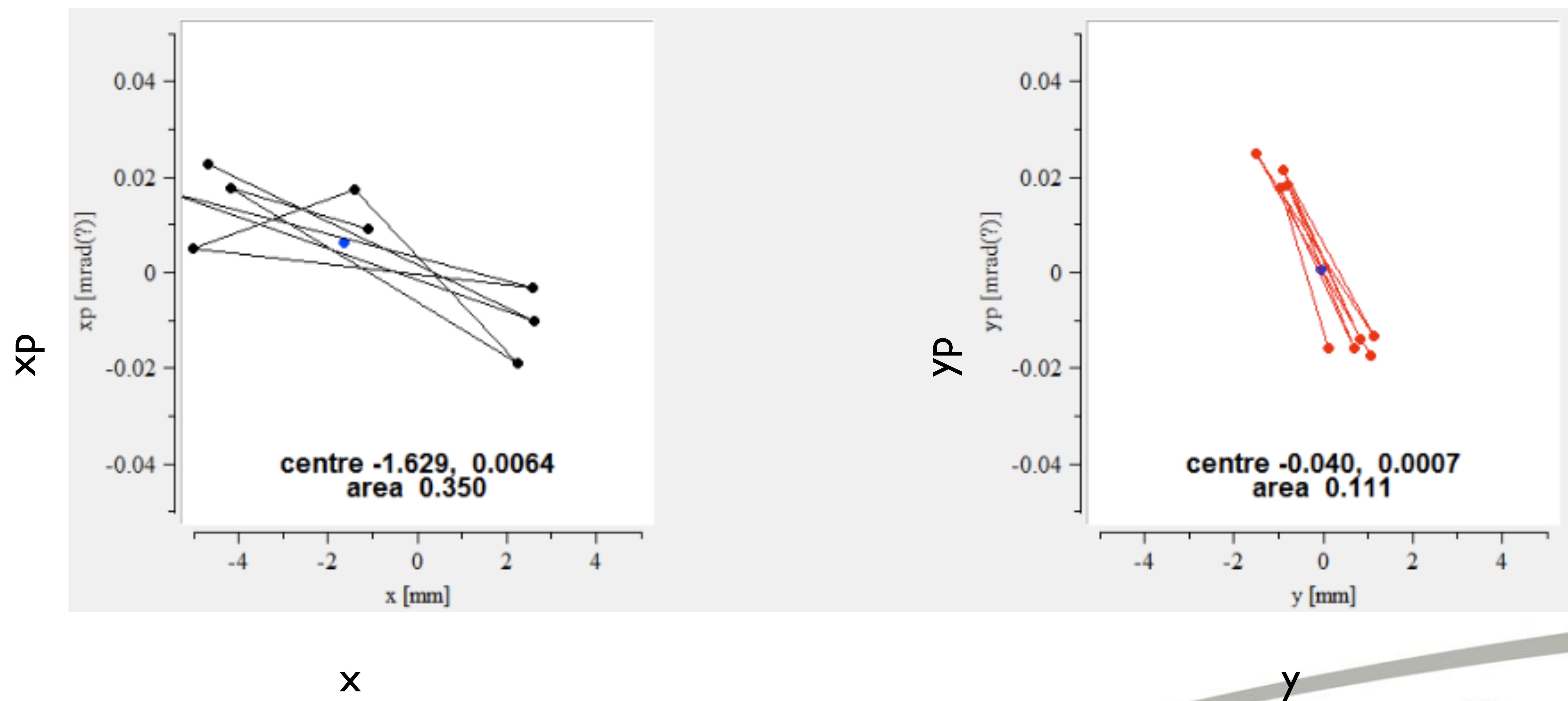
What we learned (3a)

large acceptance

Very strong focusing lattice gives huge physical acceptance, more than 1000 pi mm mrad (normalized).



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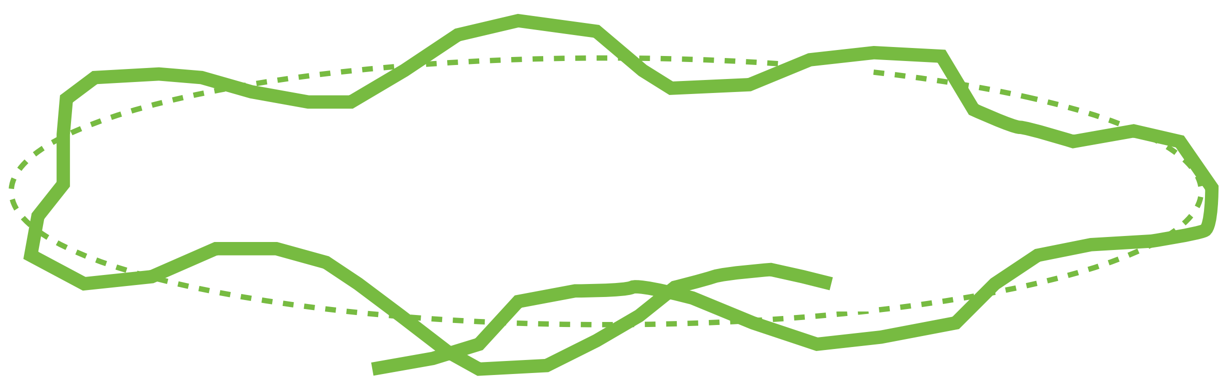
What we learned (3b)

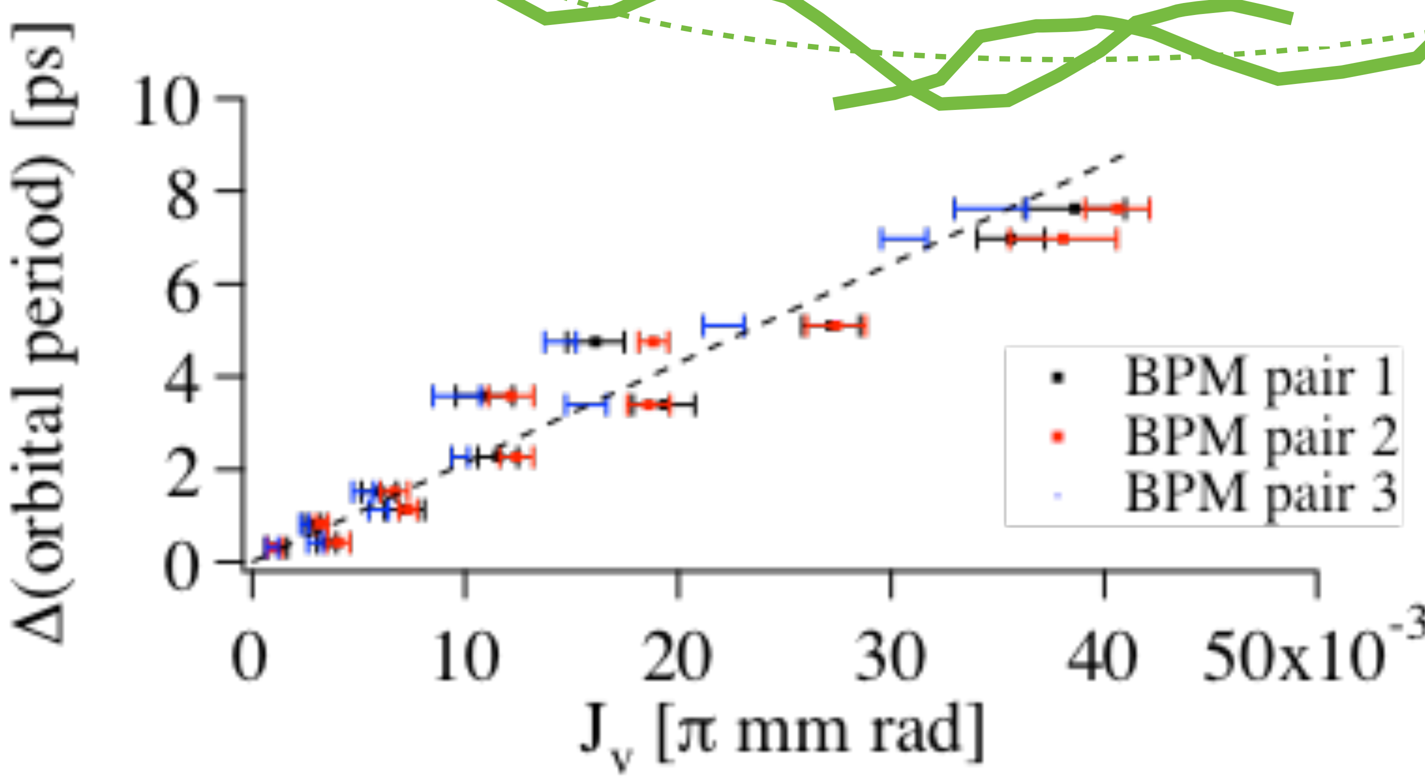
amplitude dependent orbital period

Large transverse amplitude particles circulate slower without chromaticity correction.

betatron oscillation around a ring



Large amplitude particle follow the longer path.



Shift of orbital period linearly depends on action (single particle emittance).

A paper is submitted to PRSTAB

What we learned (4a)

orbit correction

Orbit correction algorithm similar to that of synchrotron could be applied and reduced COD indeed.

Synchotron

$$\overset{n_m \times n_c}{[A]}\ \overset{n_c \times 1}{[c]} = -\overset{n_m \times 1}{[m]}$$

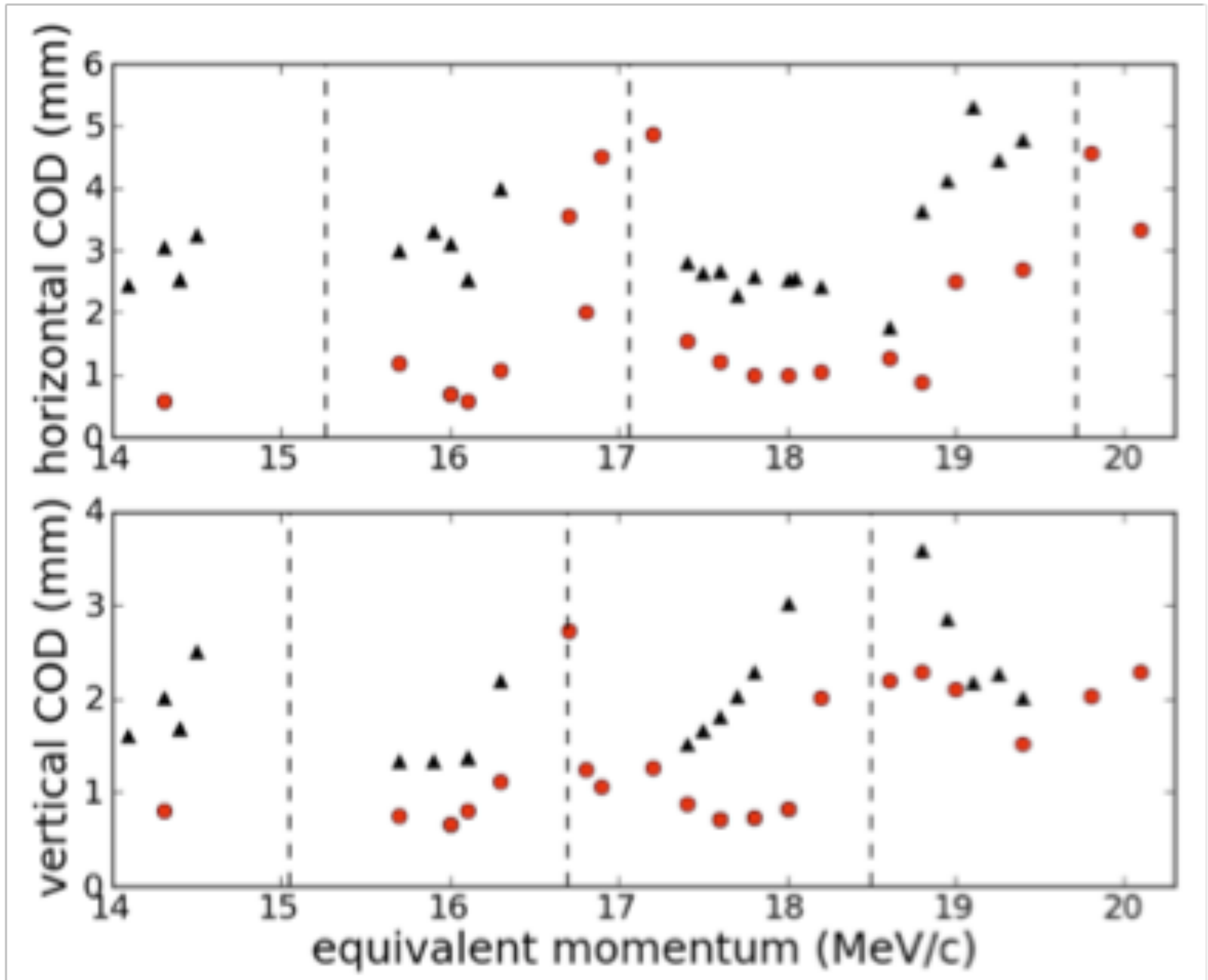
LNS FFAG

$$\overset{p \times n_m \times n_c}{\begin{bmatrix} A_{p1} \\ A_{p2} \\ \dots \\ A_{pf} \end{bmatrix}} \overset{n_c \times 1}{[c]} = - \overset{p \times n_m \times 1}{\begin{bmatrix} m_{p1} \\ m_{p2} \\ \dots \\ m_{pf} \end{bmatrix}}$$

A : response matrix

c : corrector srength

m: COD measurement



COD before (black) and after (red) correction based on response matrix measured at 14.3, 16.1 and 18.0 MeV/c and solve c by SVD.

What we learned (4b)

orbit correction

Harmonic correction is another option for linear non-scaling FFAG.

> Need enough number of correctors to cover all the harmonics (number of integer tunes).

It looks successful on paper. Unfortunately, no time to prove in EMMA.

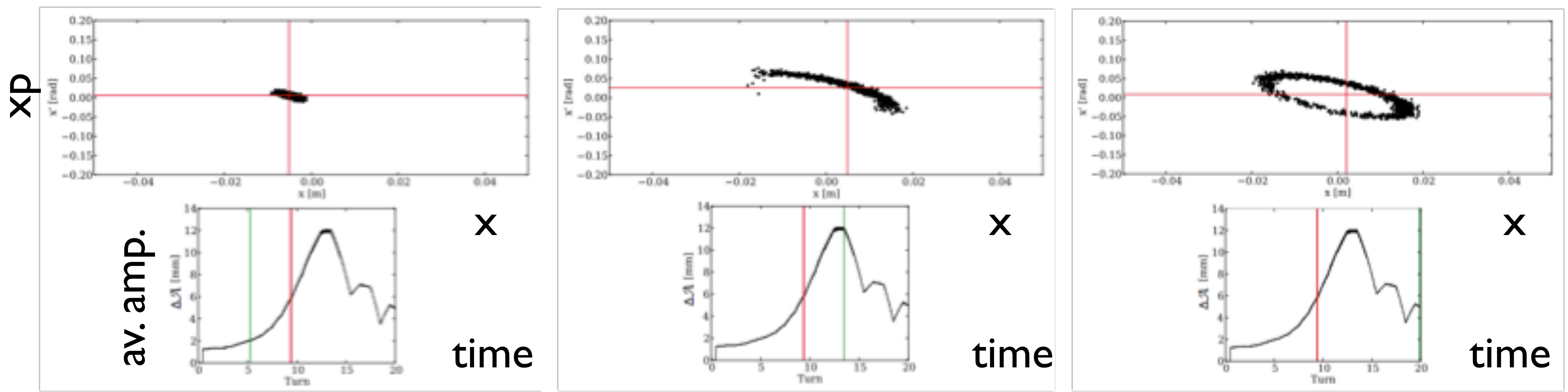
c

A paper is submitted to PRSTAB

What we learned (5)

integer tune crossing

Integer tune crossing itself is not harmful. It only excites coherent motion, not emittance growth.



before integer tune | right after integer | long after integer corssing

time

Natural chromaticity with finite momentum spread causes decoherence and emittance growth.

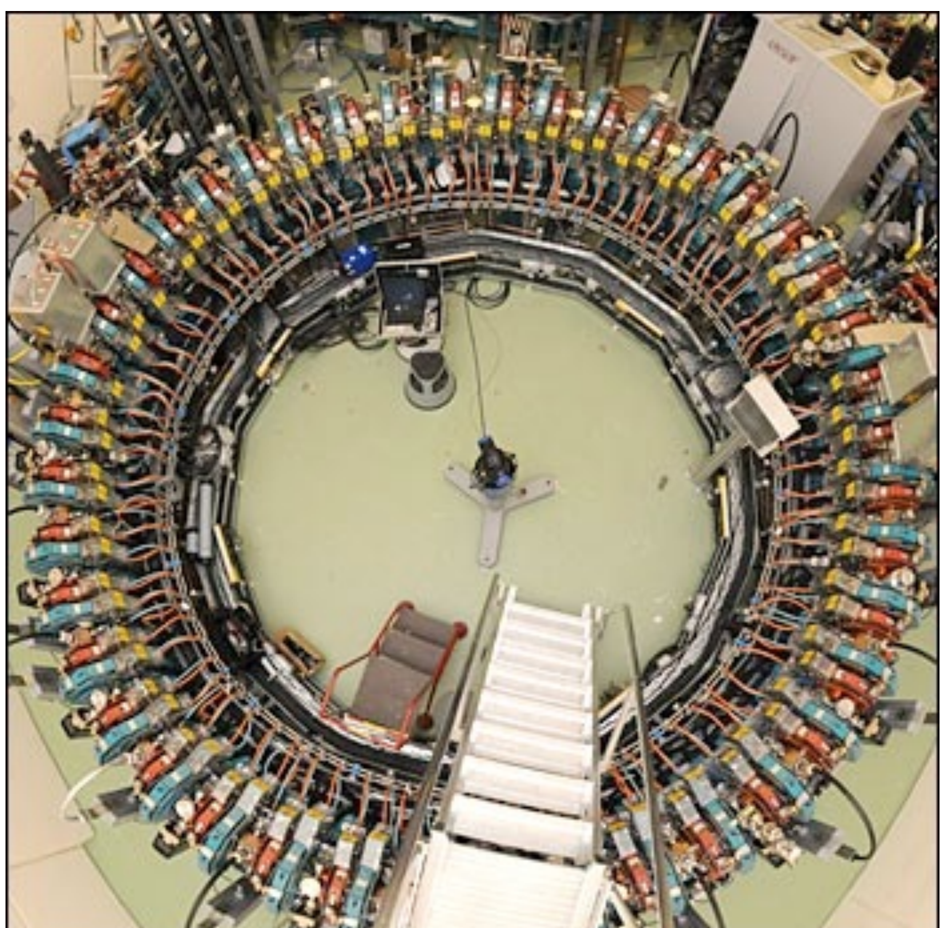
This is not the case in cyclotrons (small chromaticity).

What we learned (6)

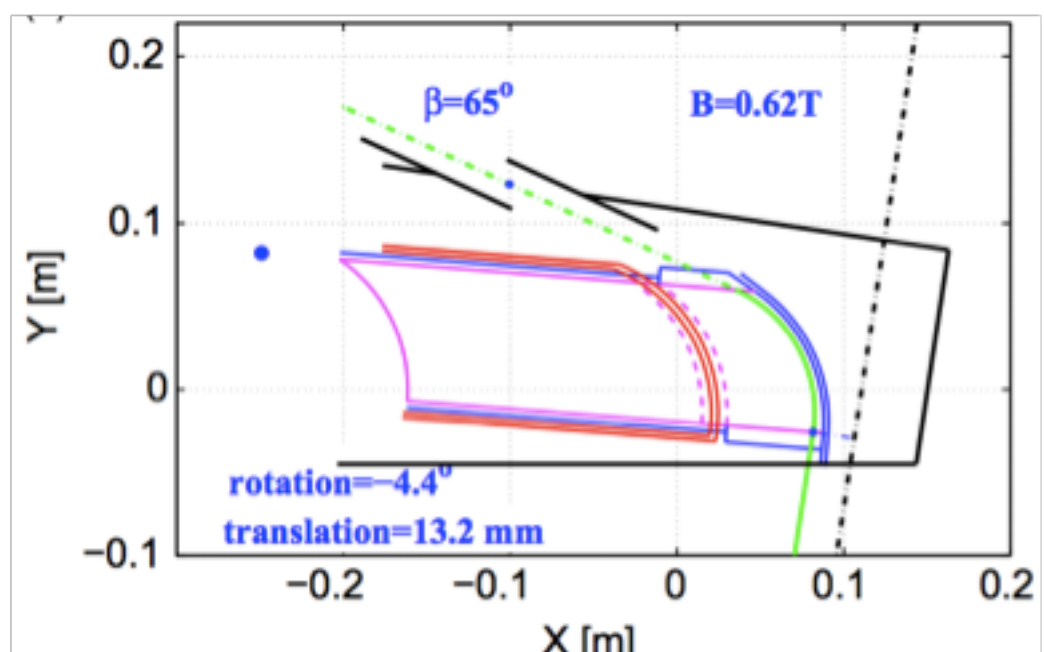
injection and extraction

Need compromise between small orbit excursion and long enough straight for injection and extraction.

EMMA may stress too much on small dispersion.



- Designs facilitating inj/ext have been found.
- Large angle septum



65 degree septum

- Insertion or superperiod

What we learned (7)

phase of 19 rf cavties

- Adjusting rf phase of 19 cavities is relatively harder because of high rf frequency of 1.3 GHz compared with more conventional frequency for cyclotron like a few 10 MHz.

What we learned (8)

beam position monitor

- The size of beam chamber is about the same as that of synchrotrons and the same type of Beam Position Monitor could be used. However, beam orbit is far off-centre by design. Accuracy and sensitivity in the entire area need to be assured.
- When the beam goes near the aperture limit, BPM does not detect beam signal.

What we learned (9)

matching at injection

- No diagnostics to detect orbit mismatch at injection.
- No diagnostics to detect optical mismatch at injection.
- YAG screen is the only devise to see the beam profile.
- Are profile monitors with multi-wire helpful?

What we learned (10)

injection line

- Orbit and optics from the injection line to the injection system (septum and kickers) are not clearly understood.
- There seems to be considerable alignment errors which induces orbit mismatch.
- Orbit in septum region (70 degree bend) is not well understood.

What we learned (11)

injection energy

- It is difficult to inject below 12.5 MeV/c.
- It is not clear whether it is a dynamic aperture problem or simply we cannot steer the beam on to the closed orbit.
  - I have succeeded in once before realignment of the all magnets.
  - This probably suggests that the problem is simply the lack of control.

Next step and possible improvements

Continuation proposal

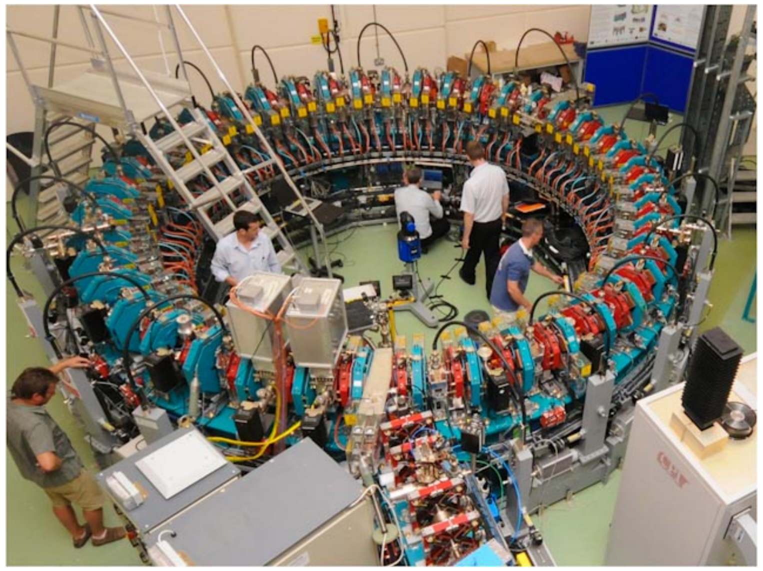
hopefully beam time will be available in future

- Identify the source of vertical COD and establish COD correction in both planes (harmonic correction).
- Aperture survey with acceleration.
- Measurement of nonlinear map experimentally.
- Explore optimised muon lattice configuration, namely QD/QF strength and position.
- Measure phase rotation with different longitudinal and transverse oscillation amplitudes (for PRISM).
- Pulse by pulse extraction with different momentum.

Summary

Good compromise between small dispersion and long straight

Much smaller magnets. "Cyclotron with synchrotron size magnets."



Almost isochronous so that fixed frequency rf system.

Resonance can be crossed during acceleration.

Much faster decoherence due to large chromaticity and more momentum spread.

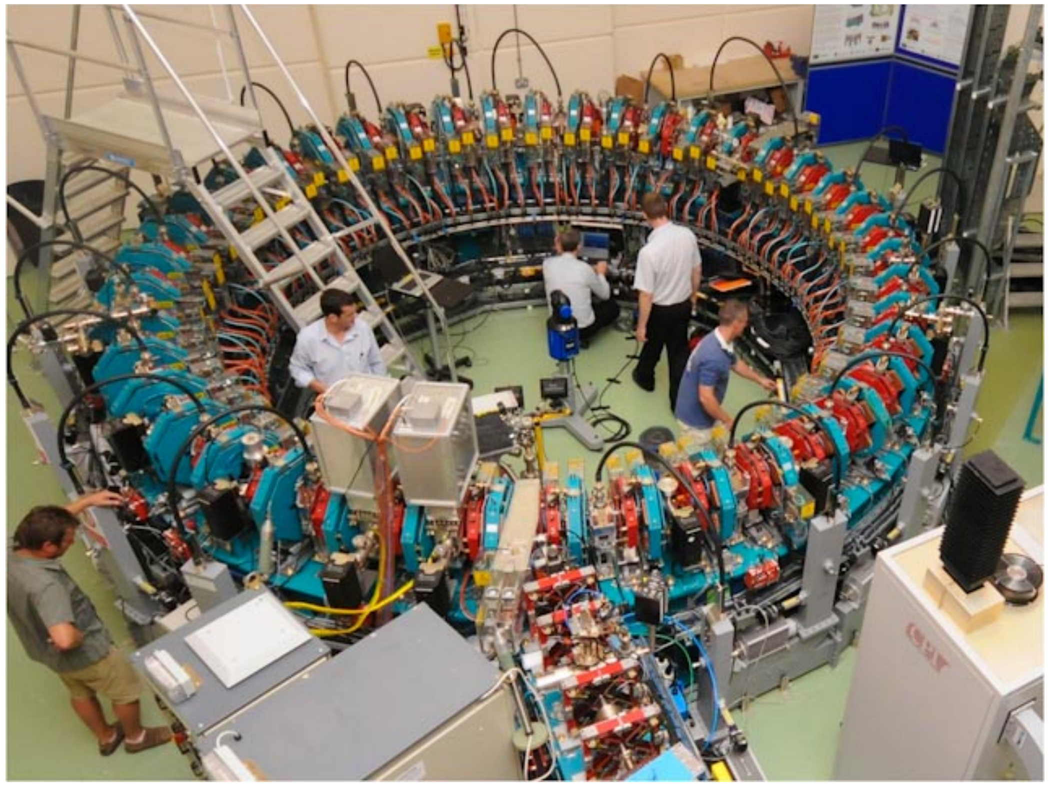
Huge acceptance.

Orbital period depends on transverse amplitude.

Same technique to restore ideal orbit as synchrotrons.

Backup slides

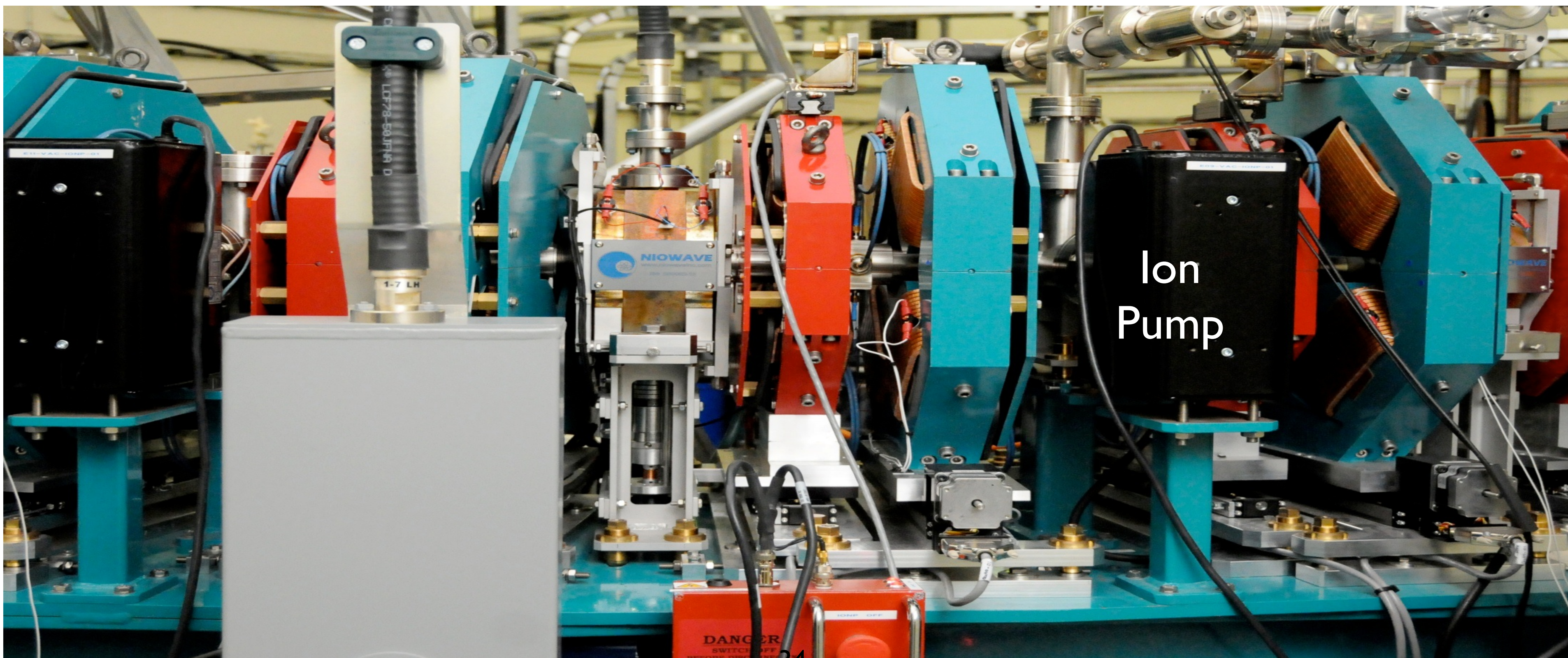
EMMA in pictures



F-QUAD

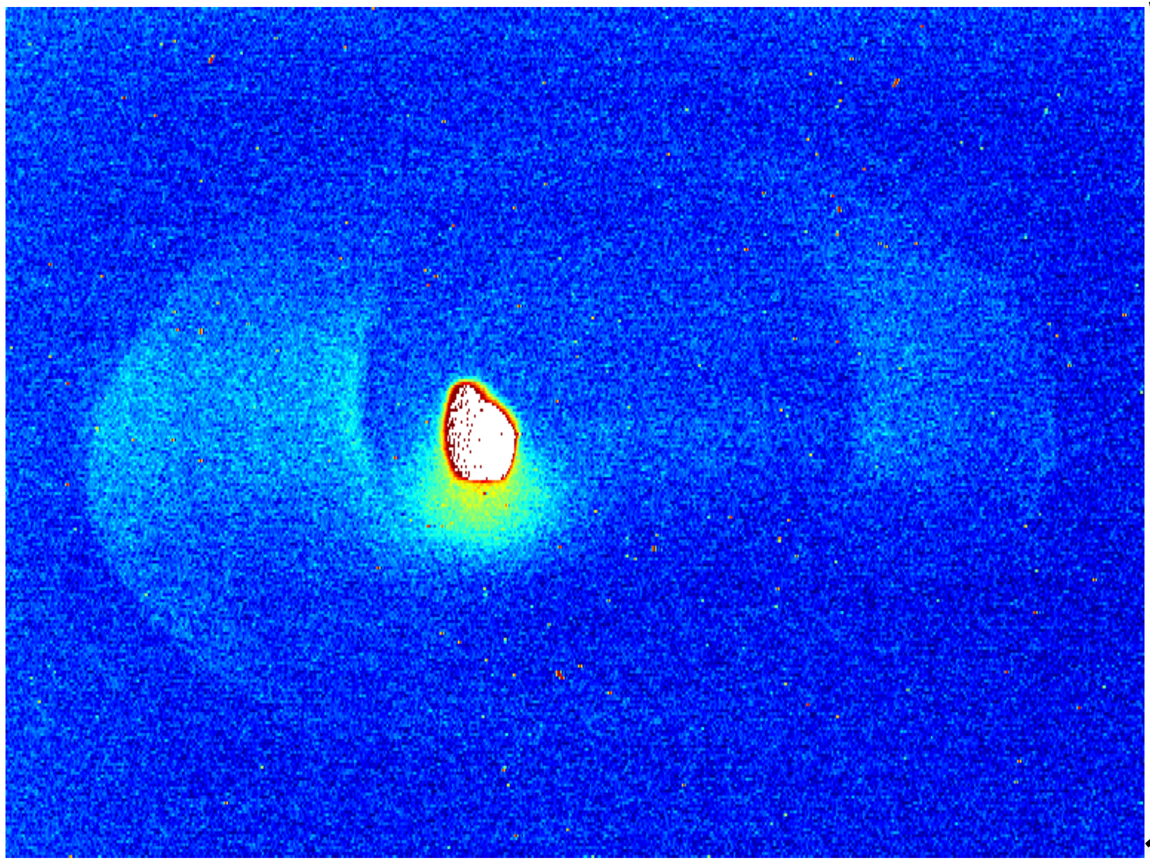
rf cavity

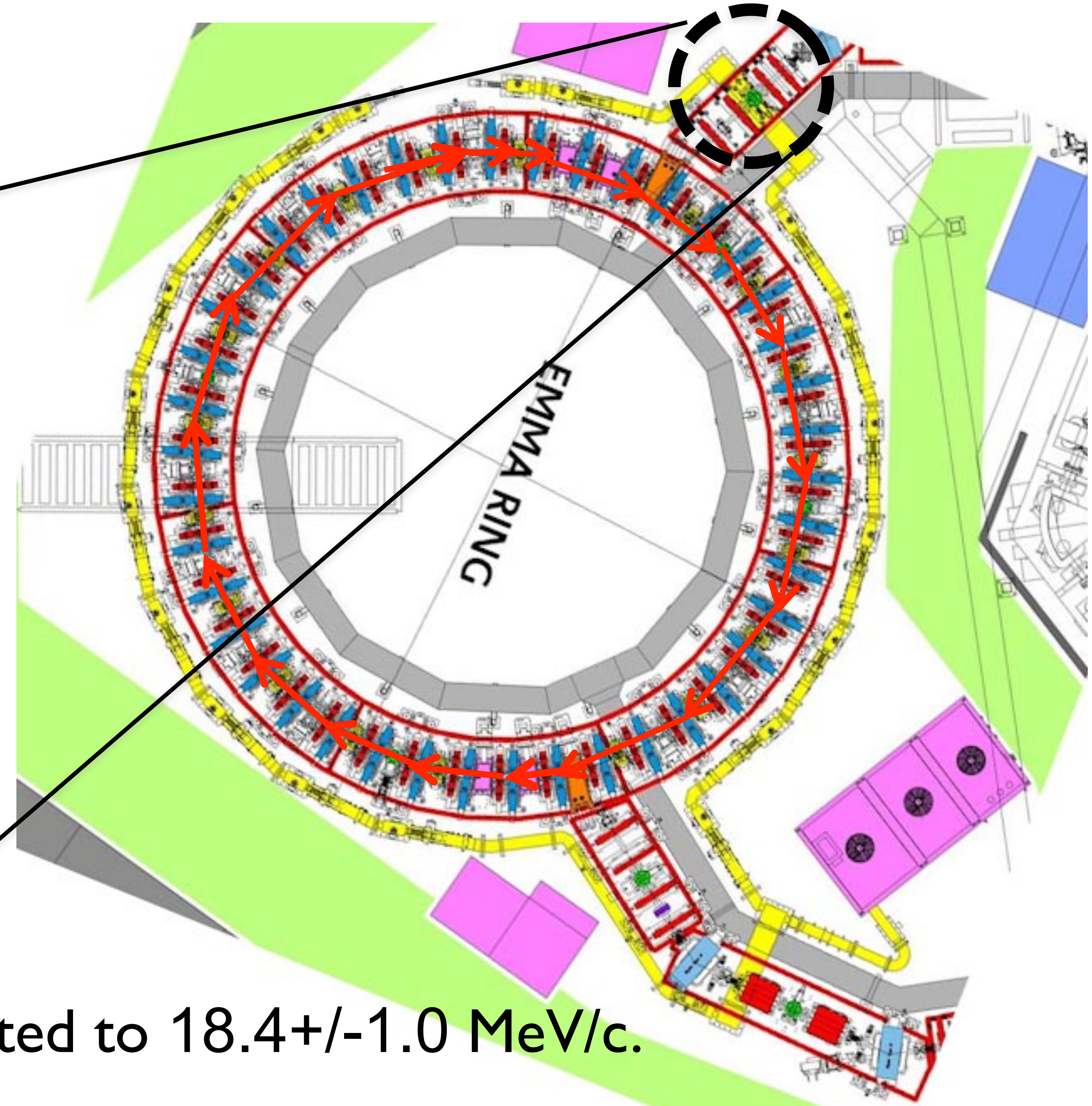
D-QUAD



Momentum measurement at extraction

Beam image after extraction
on 18 April 2011





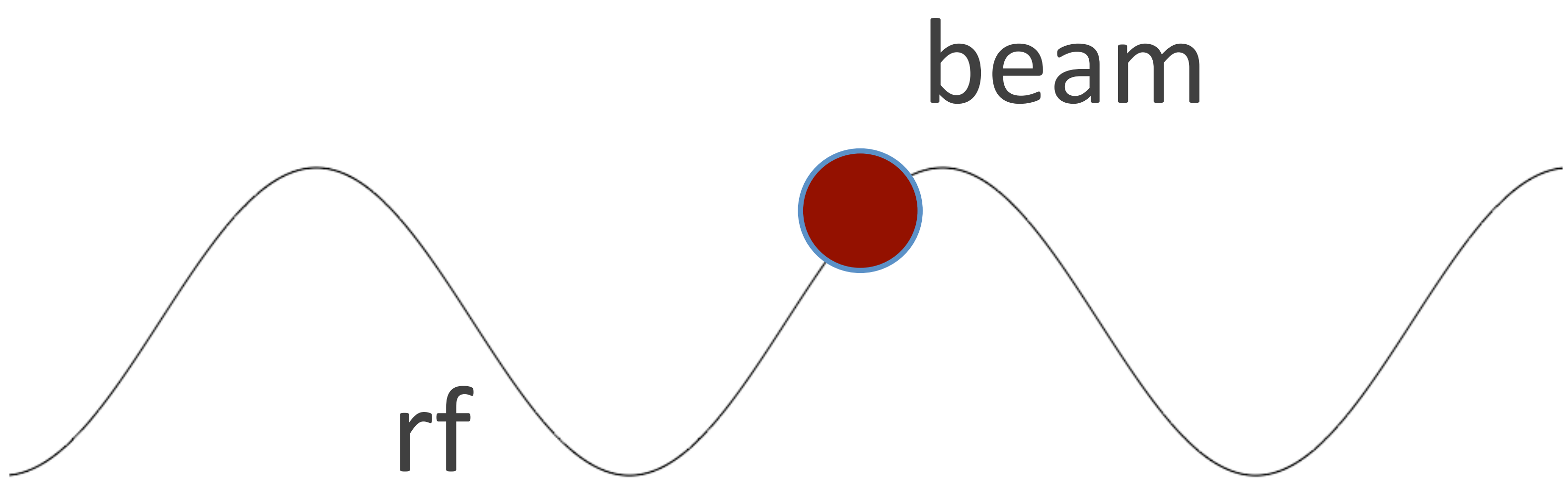
12.0+/-0.1 MeV/c beam is accelerated to 18.4+/-1.0 MeV/c.

With rf voltage of 1.9 MV

Calibration of momentum

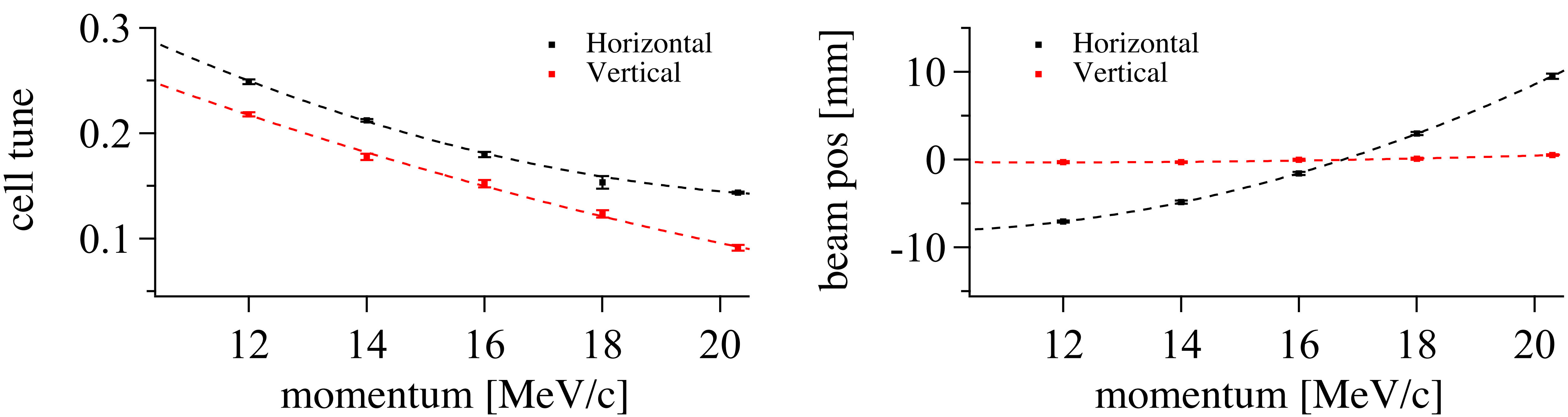
Relative phase between beam and rf waveform were directly measured by oscilloscope.

Absolute phase zero was determined by the position of stable fixed point where the beam oscillates with very small synchrotron oscillation.



Calibration of momentum

Measurement of (1) cell tune vs momentum and (2) beam position vs momentum can be used to translate from cell tune and vertical beam position to momentum.



Improvements (1)

simulation around injection system

- Alignment of septum and matching with injection line.
  - Tracking in the septum region with calculated or measured 2(3)D fields gives more accurate orbit and optics matching around the region.

Improvements (2)

injection line

- Rearrange the injection line to ease proper orbit control and optics matching at injection.
- Relocation or addition of beam position monitor at injection line.
    - Modelling of the injection system earlier discussed is the key to do this.
- Hopefully, injection below 12.5 MeV/c becomes easy.

Improvements (3)

beam position monitor

- Is there any quick fix to widen the detection area of BPM?
- Could it detect beam position with less charge?

- Electronics of BPM has to be discussed.

Improvements (4)

beam profile measurement

- Multiple beam profile monitors with proper phase advance is an option to ensure optics matching.
- Is there any other (cheap) way to make optics matching?
    - How it has been done in a cyclotron?

Improvements (5)

Online modelling with realistic fields

- Online modelling with 3D field (Zgoubi) of the whole ring (not hard edge model) will be nice.
- We should use it in parallel with beam study.